A Paradigm Shift

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Can events in the lower atmosphere (hurricanes, cyclones, thunderstorms, frontal passages, etc) and at ground level (underground nuclear explosions, earthquakes, tsunamis, etc) cause a perturbation in the electron density in the ionosphere? You bet they can. This month's column reviews some of the history and recent developments in this area.

In my early days of propagation studies in the mid to late 1990's, I wondered why our propagation predictions gave monthly median MUFs (maximum useable frequencies) and monthly median signal strengths instead of daily values. A paper in the scientific literature in 2001 by Rishbeth and Mendillo [note 1] elegantly answered my question. There were earlier papers on this subject (as referenced in the Rishbeth and Mendillo paper), but the Rishbeth and Mendillo paper was the first one I read on this subject.

The authors used 34 years of data from thirteen ionosondes to determine that the day-to-day variability of the peak F2-layer electron density is 20% during the day and 33% during the night (as defined by the percentage of the standard deviation over the monthly mean). The authors listed four major areas of possible causes for this variability:

1. *Solar ionizing radiation*	3. *Neutral atmosphere*
Solar flares	Solar and lunar tides: generated within thermosphere or coupled through mesosphere
Solar rotation (27 day) variations	Acoustic and gravity waves
Formation and decay of active regions	Planetary waves and 2-day oscillations
Seasonal variation of Sun's declination	Quasi-biennial oscillation
Annual variation of Sun–Earth distance	Lower atmosphere weather coupled through mesopause
Solar cycle variations (11 and 22 years)	Surface phenomena: earthquakes, volcanoes
Longer period solar epochs	
2. *Solar wind, geomagnetic activity*	4. *Electrodynamics*
Day-to-day 'low level' variability	Dynamo 'fountain effect' at low latitudes
Substorms	Penetration of magnetospheric electric fields
Magnetic storms	Plasma convection at high latitudes
IMF/solar wind sector structure	Field-aligned plasma flows to and from plasmasphere and protonosphere
Energetic particle precipitation and Joule heating	Electric fields from lightening and sprites

The authors reduced the four major areas to three broad categories: 'solar' (category 1 above), 'geomagnetic' (category 2 above) and 'meteorological' (category 3 and 4 above). They next analyzed the ionosonde data and determined that the day-to-day variability during the day due to solar issues was 3%, the day-to-day variability during the day due to geomagnetic issues was 13% and the day-to-day variability during the day due to meteorological issues was 15%. Since we're dealing with standard deviations, note that $(3\%)^2 + (13\%)^2 + (15\%)^2 = (20\%)^2$ [note 2].

This is an interesting result. It says the category that we probably know the most about (solar issues) contributes the least to the day-to-day variability of the ionosphere during the day (and probably during the night). Think about that. If today's 10.7 cm solar flux is a bit higher than yesterday's 10.7 cm solar flux, it doesn't necessarily mean that the ionosphere is a bit better

today. It also says chasing small changes in the 10.7 cm solar flux (or the sunspot number, for that matter) may be a futile effort due to the impact of the other two issues.

In 2018, a similar paper [note 3] by Fang, Fuller-Rowell, Yudin, Matsuo, and Vierek was published that concluded that, globally, geomagnetic activity is the main contributor to the day-to-day F2 region variability, followed by lower atmosphere perturbation, and then solar activity. Again, solar activity contributes the least to the day-to-day variability.

In 2019, Jackson, Fuller-Rowell, Griffin, Griffith, Kelly, Marsh, and Walach [note 4] published their paper titled *Future Directions for Whole Atmosphere Modeling: Developments in the Context of Space Weather*. In the Abstract is the quote:

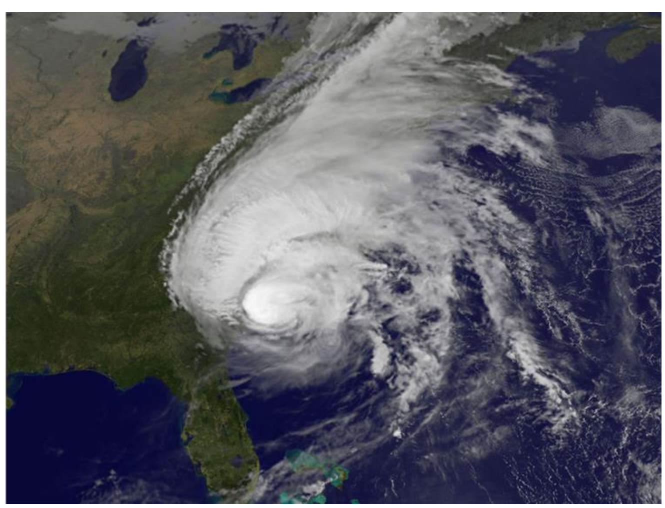
> *"With respect to predicting the state of the thermosphere and ionosphere, there has been a recent paradigm shift; it is now clear that any self-respecting model of this region needs to include some representation of forcing from the lower atmosphere, as well as solar and geomagnetic forcing."*

Thus scientists are now focusing on 'meteorological' issues [note 5] with respect to modeling the ionosphere. Hopefully this research will eventually lead to a daily physical model [note 6] of the ionosphere, which means we'll have daily propagation predictions – not monthly median propagation predictions.

Now let's look at recent papers that have investigated events in the lower atmosphere and at ground level that perturbed the electron density in the ionosphere.

<u>Hurricanes</u>

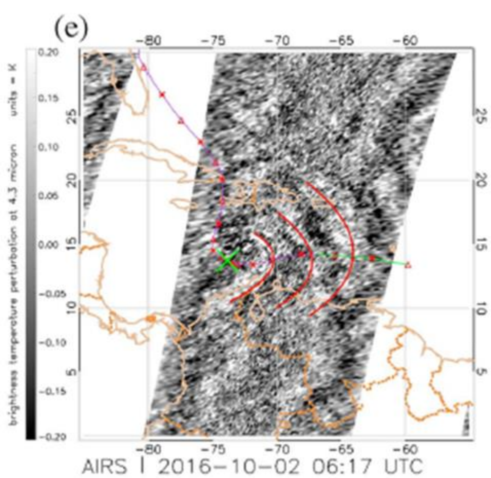
From late September 2016 thru early October 2016, Hurricane Matthew traversed the Caribbean and then up the East Coast of the United States. The left image shows Hurricane Matthew's track (along with its intensity), and the right image is a visual image as it went up the East Coast. As can be seen, when Hurricane Matthew was in the Caribbean, it grew to Category 5.

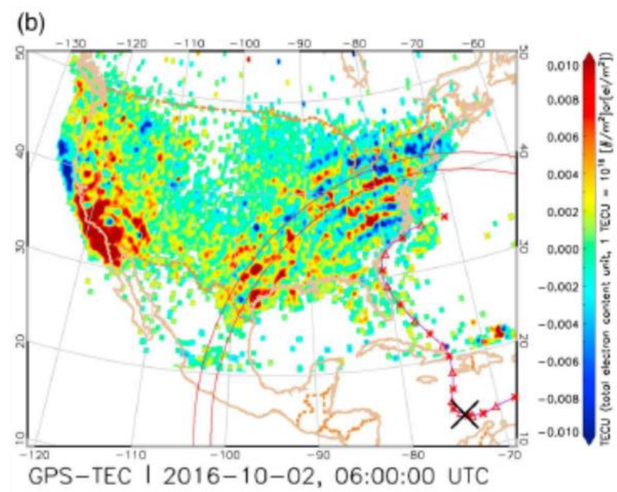


In 2019, Xu, Yue, Xue, Vadas, Miller, Azeem, Straka, Hoffman and Zhang [note 7] used space-borne satellites to observe the stratosphere and the mesosphere and used GPS ground receivers to observe the ionosphere in the Caribbean to ascertain the impact of Hurricane Matthew.

They found that Hurricane Matthew excited a large number of gravity waves (GWs), with horizontal wavelengths of approximately 200-300 km in the stratosphere (~ 30-40 km height) and in the mesopause (~ 85-90 km height) in the Caribbean. These gravity waves then likely propagated upwards into the ionosphere, where traveling ionospheric disturbances (TIDs) of approximately 250-350 km horizontal wavelengths (at 100-400 km heights) were observed.

The following images are from the referenced paper. The image on the left (Figure 3e in the paper) shows concentric temperature perturbations in the 4.3 um band from the Atmospheric Infrared Sounder satellite (highlighted with red lines) about the center of the hurricane (the green x). The image on the right (Figure 8b in the paper) shows concentric TEC (total electron content) perturbations (highlighted with red lines) about the center of the hurricane (the black x). The images are at approximately the same time on the same day.





The authors concluded that Hurricane Matthew induced significant dynamical coupling between the troposphere and the entire middle and upper atmosphere via GWs. The authors believe their paper is the first comprehensive satellite analysis of gravity wave propagation generated by a hurricane from the troposphere through the stratosphere and mesosphere into the ionosphere.

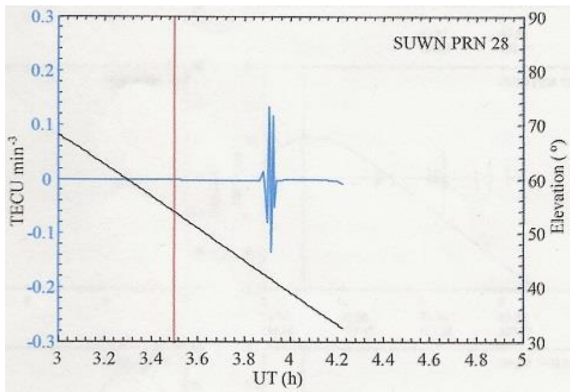
Underground Nuclear Explosions

On September 3, 2017, North Korea detonated an underground nuclear device at approximately 41.35° N and 129.11° E (geographic coordinates) at 03:30:01 UTC. Scientists from China investigated the impact of this explosion on the ionosphere [note 8] using TEC data from the GPS system.

As expected, the authors saw the signature of the underground nuclear explosion (UNE) in the TEC data. But that simple sentence does not adequately describe the mathematical effort needed to extract this signature from the data. To calculate the ionospheric disturbance related to the

UNE from GPS observations, the main trends of the relative slant TEC that are strongly influenced by the Sun's diurnal cycle needed to be removed (geomagnetic activity was low).

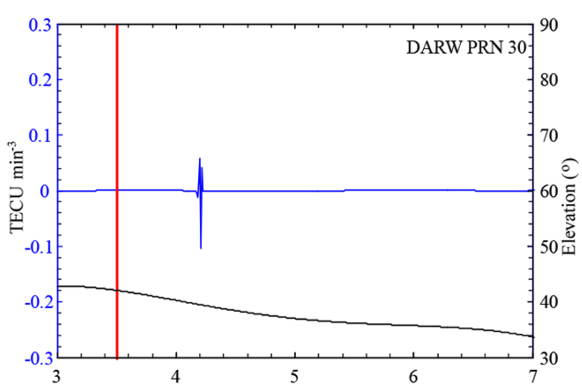
The authors had to take the third derivative of the slant TEC data versus time to emphasize the more significant wave components with small amplitudes. Finally, the background noises of the third-order derivatives were removed using the Haar wavelet decomposition process (see Haar wavelet at Wikipedia). Here's the result (from Figure 3d in the paper) for the signature at an observatory 363 km from the UNE.



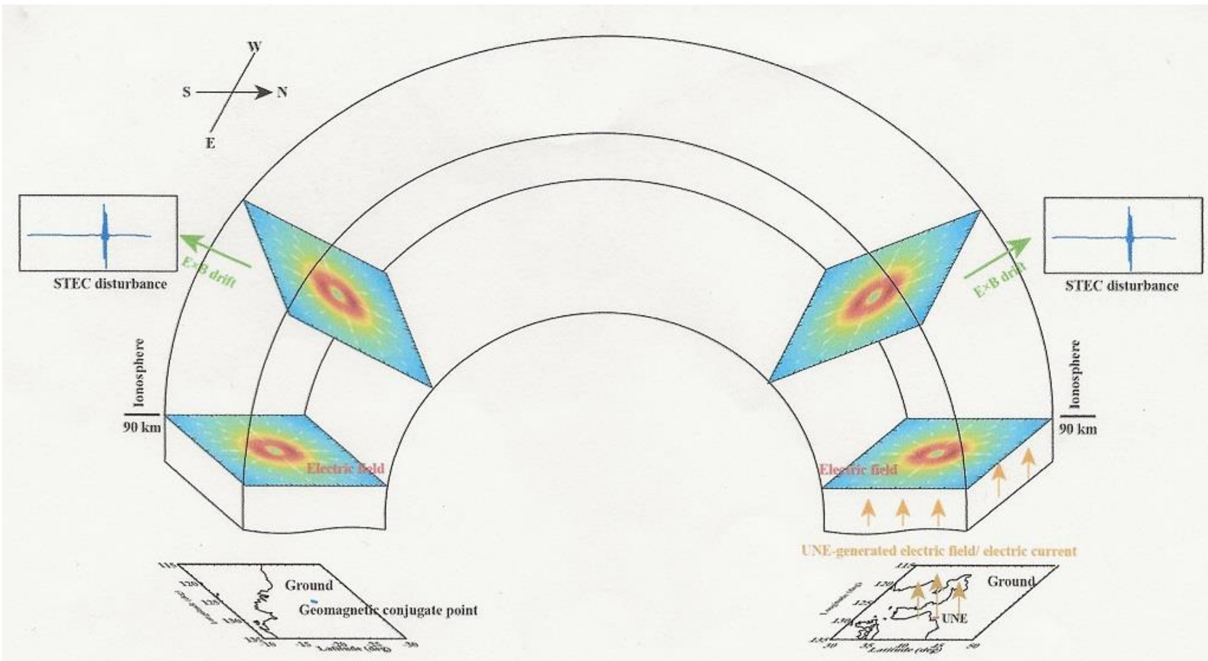
The red vertical line is the time of the UNE. The blue trace is the signature in the ionosphere. See the paper for a description of the black line. Using the distance of 363 km and the time difference between the UNE (3.5 hrs UTC) and the observatory (3.86 hrs UTC) indicates the disturbance from the UNE "propagated" at about 280 meters/second.

So what was the "propagation" mode of the ionospheric signature? The ionospheric disturbance doesn't look like a traveling ionospheric disturbance as in the previous hurricane study. The authors believe the "propagation" mode is more tied to electric field penetration up to the ionosphere rather than a gravity wave. An interesting side note to the electric field hypothesis is that there is high conductivity along geomagnetic field lines, which suggests that the disturbance could be mapped to the geomagnetic conjugate point.

The geomagnetic conjugate of the UNE location would roughly be along the same longitude and somewhat south of Darwin (Northern Territory), Australia. Here's the result for TEC perturbations at Darwin (Figure 4 in the paper).



Interesting, isn't it? Thus the TEC perturbations in the ionosphere were seen near the UNE and at the UNE's geomagnetic conjugate point. The following sketch (Figure 8 in the paper) shows this general scenario.



Earthquakes

The April 25, 2015 Nepal earthquake (magnitude 7.8) at 0612 UTC attracted the attention of many scientists. Let's look at two papers that looked at this earthquake.

The first paper [note 9] investigated electromagnetic precursors of the Nepal earthquake and their possible effect on the ionosphere. This is a major area of study nowadays – are there precursors to an earthquake that would warn us of the impending catastrophe?

The authors analyzed measurements from three different techniques prior to the earthquake:

1. Subsurface VLF (3.012 kHz) electric field measured with the help from a borehole antenna
2. TEC of the ionosphere measured with a GPS receiver
3. VLF amplitude measured of the received signal from a military transmitter at 19.8 kHz

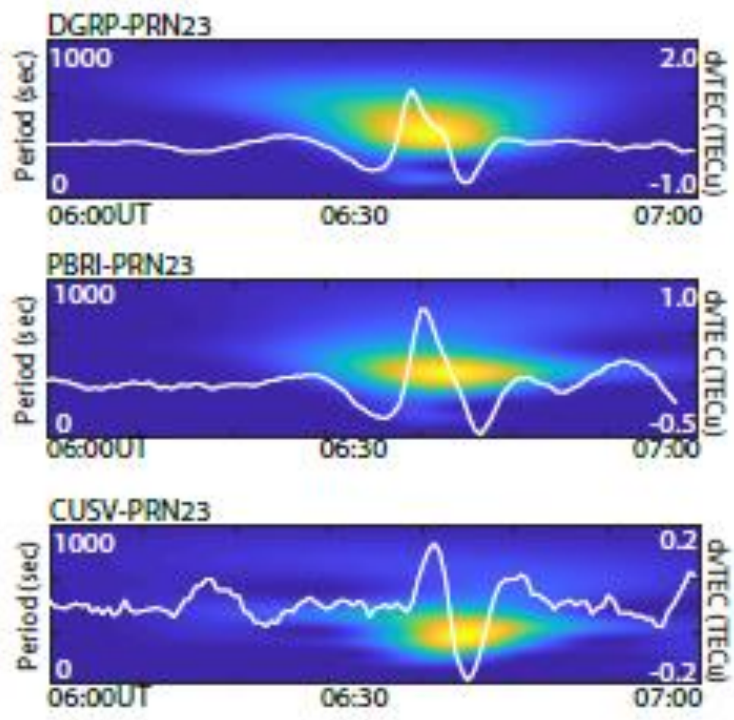
The subsurface VLF electric field measurements showed an anomalous increase 14 days prior to the main shock. The TEC data showed enhanced TEC variation between 6 and 15 days prior to the main shock. Unfortunately there were hardware problems with monitoring of the amplitude variation of the 19.8 kHz signal from the military transmitter, and no data was collected.

The authors discussed three possible "propagation" modes:

1. Ionization of the near Earth's atmosphere over the seismic zones by radon gas and creating a large scale electric field
2. Gravity waves
3. An anomalous trough in the variation of atomic oxygen ion and molecular ion over the epicenter of large magnitude earthquakes

The second paper [note 10] investigated possible ionospheric responses to gravity waves generated by surface displacements. The epicenter of the Nepal earthquake occurred at the Main Himalayan Thrust, and it triggering around 4000 landslides and more than 3000 aftershocks within 45 days of the event. Vertical surface displacements were around 1.6 meters from trough-to-peak, with vertical velocities up to 64 cm/sec.

The following image shows amplitudes of the vertical TEC perturbations (in TEC units) at three observation stations about 1400 km from the epicenter. Remember that the earthquake occurred at 0612 UTC. Dividing 1400 km by an average propagation time of 28 minutes (0612 to 0640) gives a velocity of about 1 km/sec.

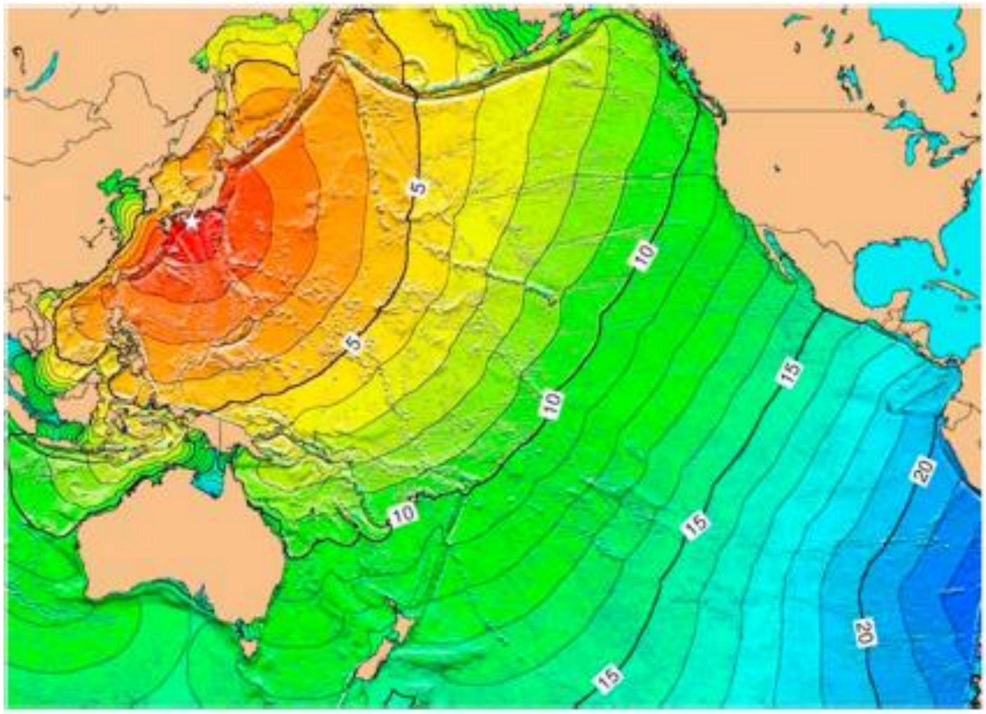


<u>Tsunamis</u>

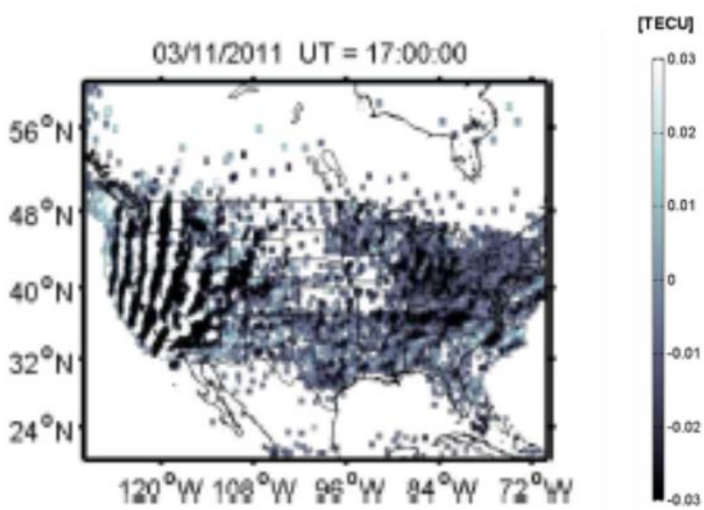
In 2017, a paper titled *Traveling ionospheric disturbances over the United States induced by gravity waves from the 2011 Tohoku tsunami and comparison with gravity wave dissipative theory* was published [note 11]. The authors investigated the March 11, 2011 Tohoku earthquake (magnitude M9.0) at 0536 UTC in Japan which generated a massive tsunami (9 meter high

waves) that launched intense atmospheric gravity waves. The tsunami waves traveled across the Pacific basin to Alaska and down the Pacific coast of North and South America.

The following image (Figure 2 in the paper) shows the propagation times (in hours) of the tsunami across the pacific. Note the concentric arcs from the epicenter of the earthquake and that the tsunami arrived on the US West Coast from 10.5-12 hours after the earthquake.

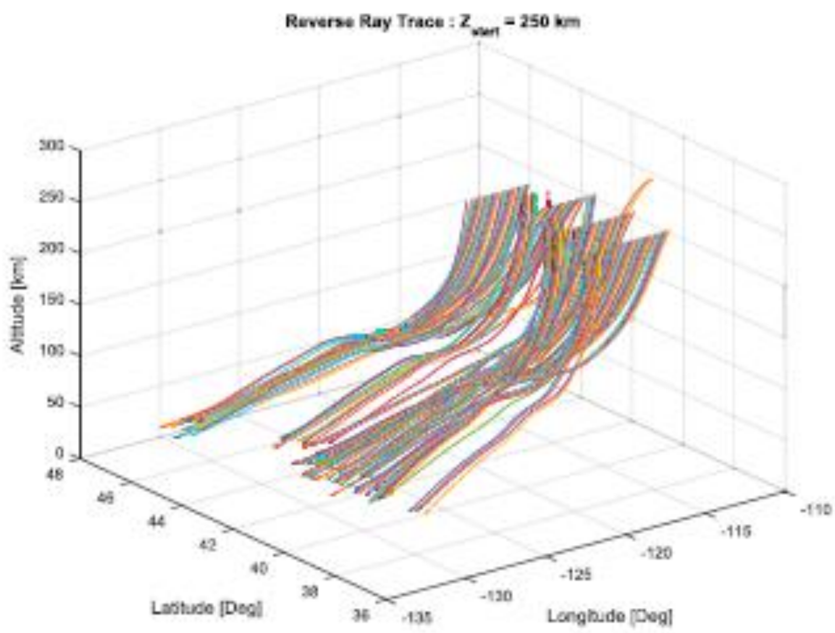


Using TEC data, the authors presented TEC perturbation data at 1530 UTC, 1645 UTC, 1700 UTC and 1915 UTC. The following image (Figure 4 in the paper) shows the TEC perturbations at 1700 UTC (11 hours and 15 minutes after the earthquake). Note that the alignment of the perturbations are similar to the concentric pattern of the tsunami arrival times.



The authors pointed out that near the epicenter of the earthquake, the observed ionospheric perturbations are a mix of waves generated by the earthquake and tsunami. The authors further stated that the tsunami was the source of intense atmospheric gravity waves generated just above the ocean-atmosphere interface, and as these gravity waves propagated across the Pacific Ocean they coupled up into the ionosphere to cause the TEC perturbations on the US West Coast.

To back up that last sentence, the authors presented an interesting analysis (Figure 10 in the paper) of how gravity waves propagated across the Pacific Ocean. The gravity waves started at low altitudes on the Japan end and rose to ionospheric altitudes on the US West Coast end.



Final Comments

a) We’ve looked at a number of events in the lower atmosphere and at ground level, and there’s evidence that at least two processes can couple these events up to the ionosphere – gravity waves and electric field penetration. There may be more, and I’m sure we’ll see more research in this area in order to eventually (hopefully!) come up with parameters that define these processes and result in daily propagation predictions. It may not happen in my lifetime, but it may for those of you younger hams.

b) These events can affect the ionosphere out to hundreds of kilometers – maybe even more if the electric field penetration process propagates along magnetic field lines to the geomagnetic conjugate of the source location.

c) Seeing the effects of the events in the ionosphere may be tough, and may require much math to extract the desired signal from the background “noise”.

d) Do these events cause noise at HF? None of the articles referenced herein mentioned noise at HF, but they weren't looking for it. We know that events in the lower atmosphere (hurricanes, cyclones, thunderstorms, frontal passages, etc) can cause noise at HF due to lightning discharges. But noise at HF from ground level events (underground nuclear explosions, earthquakes, tsunamis, etc) is still an open question as far as I'm aware. If these ground level events do cause noise at HF, how do you separate this noise from man-made noise (especially if you're using a vertical in or near an industrial area) and from auroral activity noise (especially if you're at the higher latitudes nearer the auroral zone)?

e) Several hams of the HamSCI group (Ham Radio Science Citizen Investigation – www.hamsci.org) are also getting involved in this area. For example, Diego KD2RLM and Nathaniel W2NAF are looking to see if TIDs can be seen in the RBN (reverse beacon network – www.reversebeacon.net) data. Another HamSCI participant is Larisa Goncharenko – she is a research scientist at the MIT Haystack Observatory in Massachusetts and she gave a presentation on events in the lower atmosphere and ground level events at the March 2019 HamSCI Workshop at Case Western Reserve University.

f) Over the past couple years, Larry N6NC and I collected data on several events. Appendices A, B and C (after the Notes section) details three of these events. We tried to download atmospheric data and concurrent ionosonde data, but trying to catch an event in the atmosphere showing gravity waves and then downloading nearby ionosonde data proved to be tough! Unfortunately our data is kind of sketchy.

Notes

1. H. Rishbeth, M. Mendillo, Patterns of F2-layer variability, *Journal of Atmospheric and Solar-Terrestrial Physic***s**, 63 (2001) 1661-1680

2. For the record, I reviewed this paper in my August 2004 Propagation column in the old printed WorldRadio magazine. This column is on my web site https://k9la.us in the General link (Day-to-Day Variability of the Ionosphere).

3. Tzu-Wei Fang, Tim Fuller-Rowell, Valery Yudin, Tomoko Matsuo, and Rodney Viereck, Quantifying the Sources of Ionosphere Day-to-day Variability, *Journal of Geophysical Research: Space Physics* (2018), https://doi.org/10.1029/2018JA025525

4. Jackson, D.R., Fuller-Rowell, T.J., Griffin, D.J., Griffith, M.J., Kelly, C.W., Marsh, D.R., & Walach, M.-T. (2019). Future directions for whole atmosphere modeling: Developments in the context of space weather. *Space Weather*, 17, 1342-1350. https://doi.org/10.1029/2019SW002267

5. One of the problems with ‘meteorological’ issues is coming up with a parameter to define these events. We have the K index (and other similar indices) for geomagnetic activity and 10.7 cm solar flux/sunspot number/EUV (and other similar indices) for solar activity. We don’t yet have a parameter for ‘meteorological’ issues, and it may have to be more than one parameter.

6. With respect to empirical models, ionospheric scientists are working on assimilating real-time ionosonde and/or TEC data into the International Reference Ionosphere (IRI) to move its monthly median model closer to a daily model. The IRI Real-Time Assimilative Modeling assimilates real-time measurements of foF2, hmF2, Bo and B1 from 40+ digisonde stations. More measurements are planned to be added.

7. Shuang Xu, Jia Yue, Xianghui Xue, Sharon L. Vadas, Steven D. Miller, Irfan Azeem, William Straka III, Lars Hoffman Simin Zhang (2019). Dynamical Coupling Between Hurricane Matthew and the Middle to Upper Atmosphere via Gravity Waves. *Journal of Geophysical Research: Space Physics* (2019), https://doi.org/10.1029/2018JA026453

8. Yi Liu, Chen Zhou, Qiong Tang, Guanyi Chen, and Zhengyu Zhao (2019). Geomagnetic conjugate observations of ionospheric disturbances in response to a North Korean underground nuclear explosion on 3 September 2017. Annales Geophysicae, 37, 337-345, https://doi.org/10.5194/angeo-37-337-2019

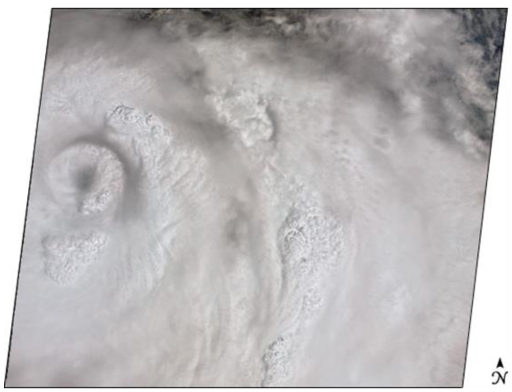
9. Sarita Sharma, Raj Pal Singh, Devbrat Pundhir, Birbal Singh, A multi-experiment approach to ascertain electromagnetic precursors of Nepal earthquakes, Journal of Atmospheric and Solar-Terrestrial Physics 197 (2020), https://doi.org/10.1016/j.jastp.2019.105163.

10. P.A. Inchin, J.B. Snively, M.D. Zettergren, A. Komjathy, O.P. Verkhoglyadova, S. Tulasi Ram, 2015 Nepal Mw7.8 Gorkha earthquake, Journal of Geophysical Research: Space Physics (2020), https://doi.org/10.1029/2019JA027200.

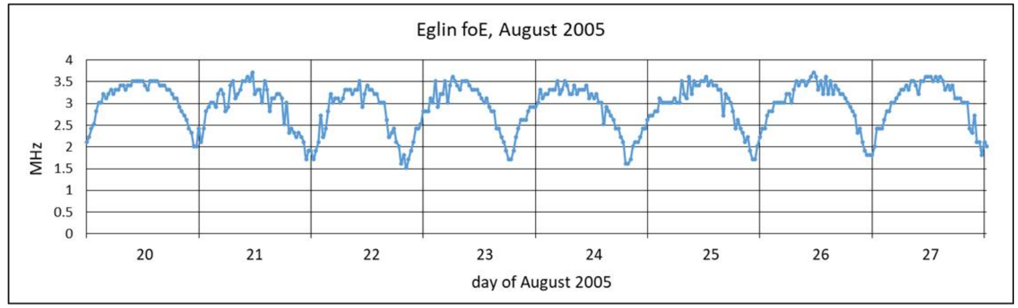
11. Azeem, I., S. L. Vadas, G. Crowley, and J.J. Makela (2017), Traveling ionospheric disturbances over the United States induced by gravity waves from the 2011 Tohoku tsunami and comparison with gravity wave dissipative theory, *J. Geophys. Res. Space Physics*, *122*, 3430-3447, doi:10.1002/2016JA023659.

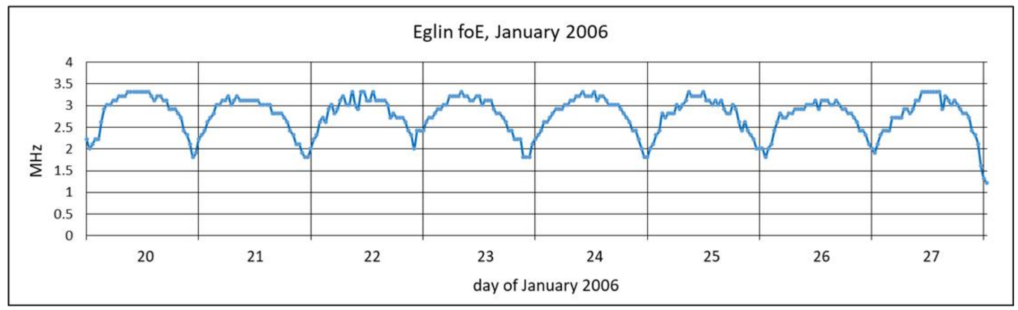
Appendix A – Hurricane Katrina – August 2005

Hurricane Katrina track

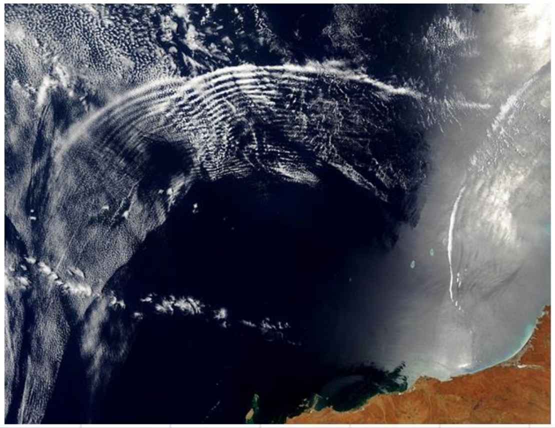


concentric gravity waves about the eye



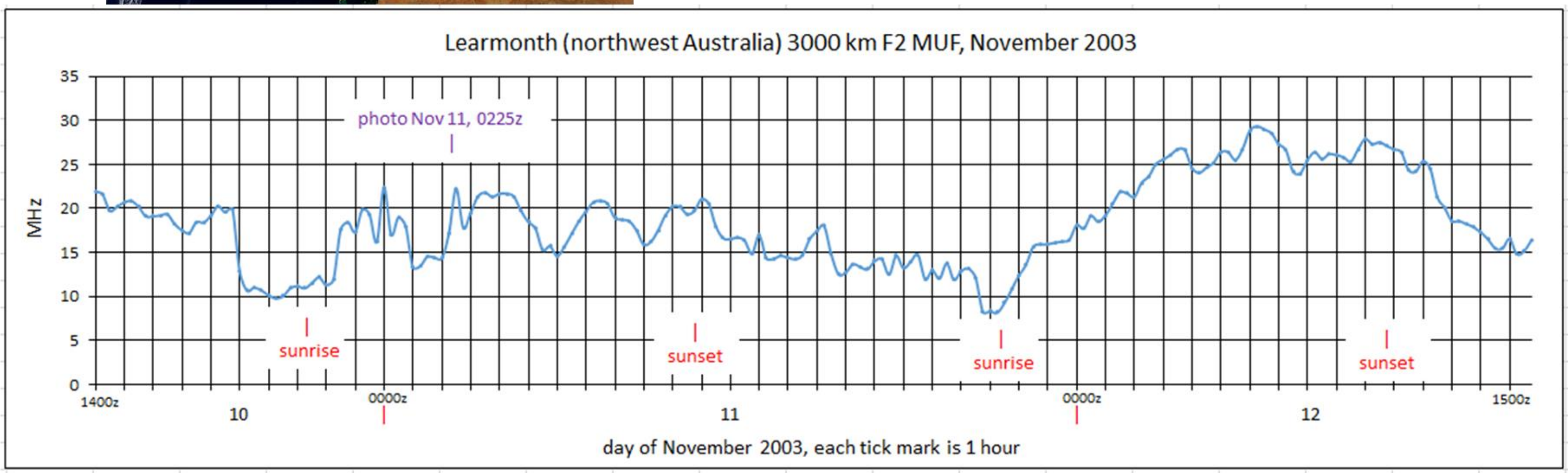


Eglin AFB ionosonde data during Hurricane Katrina (top) and data for the non-hurricane season (bottom) – TIDs are more prominent during the hurricane



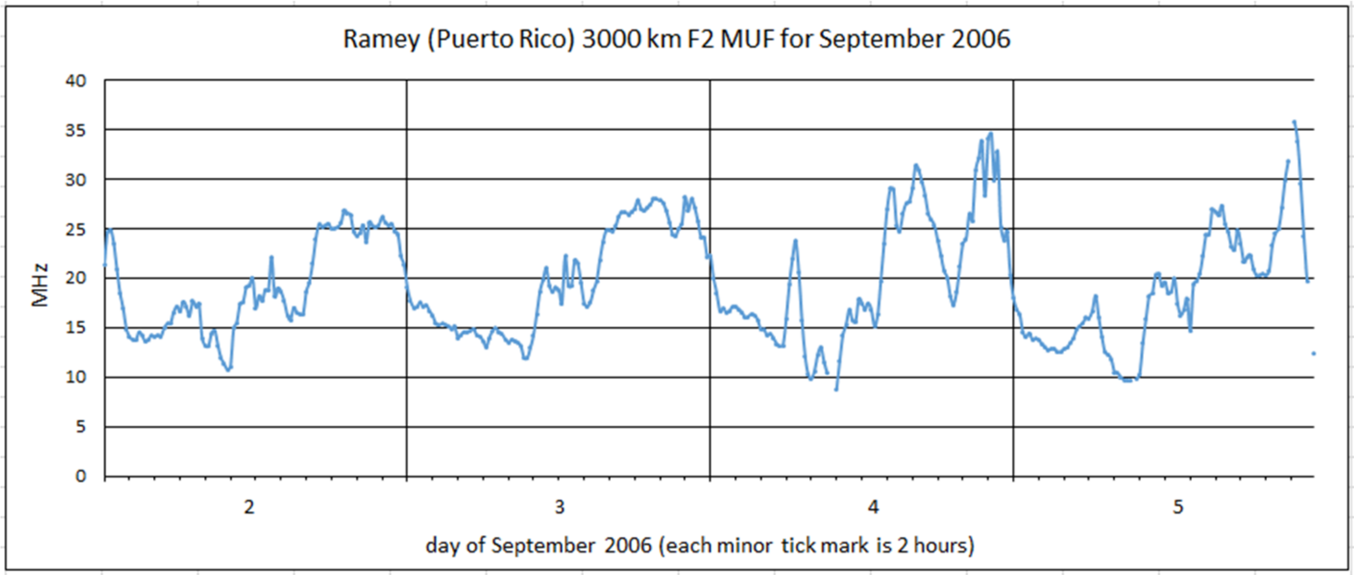
note the gravity waves
in the cloud formation

Appendix B – Weather in the Indian Ocean northwest of Australia on November 11, 2003 at 0225 UTC



Learmonth (northwest Australia) ionosonde data – TIDs are prominent around the time of the weather photo

Appendix C – Hurricane Ernesto – late August 2006/early September 2006



much TID activity